



Creep Simulation of Nuclear Fuel Cladding under long term storage conditions with TRANSURANUS

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1 Introduction

The code TRANSURANUS [1] of the Institute for Transuranium Elements (ITU) is widely used by European nuclear research institutes, nuclear industry and nuclear regulatory authorities to simulate the mechanical, thermal and physical behaviour of fuel rods in nuclear reactors. Within a joint research project between the Institute for Energy (IE) and ITU on the integrity of spent nuclear fuel cladding the idea came up to use TRANSURANUS to simulate creep processes of cladding tubes for long term storage of spent nuclear fuel. The claddings in long-term storage today are assumed to have sufficient safety margins against cladding failure but this may change if storage times are extended to hundred years or more and with higher burn-up or new fuel types which increase the temperature and irradiation levels. The creep models implemented in TRANSURANUS are intended for creep during reactor operation where the cladding is exposed to a typical temperature of 400°C; in normal reactor operation the temperature range is limited and the fuel stays in the reactor for a few years. For dry storage conditions the temperature is initially somewhat below 400°C but decreases monotonically as Figure 1 shows. The temperature drops from typically 350°C to 250°C during the first ten years and the internal pressure from fission gases drops from 6 to 5 MPa. The stresses are approximately equal to $p \cdot D/2t$ where D is the tube diameter and wall thickness respectively. A typical value for D/t is 20 but it could be as low as 40. Hence stresses would be typically 50 or 100 MPa respectively [2]. For long storage times there may also be additional pressure from Helium by decay of alfa-emitters [3]. For uranium dioxide fuel the additional pressure could be 1 MPa and 2 MPa after 100 and 300 years respectively. For MOX fuel, which contains more alfa emitters, the helium pressure could be significantly higher: 7 and 12 MPa after 100 and 300 years [3]. Hence in long-term storage the temperature range is rather large and the duration that one needs to consider is much longer. In extreme cases of long-term storage several hundred years may be considered.

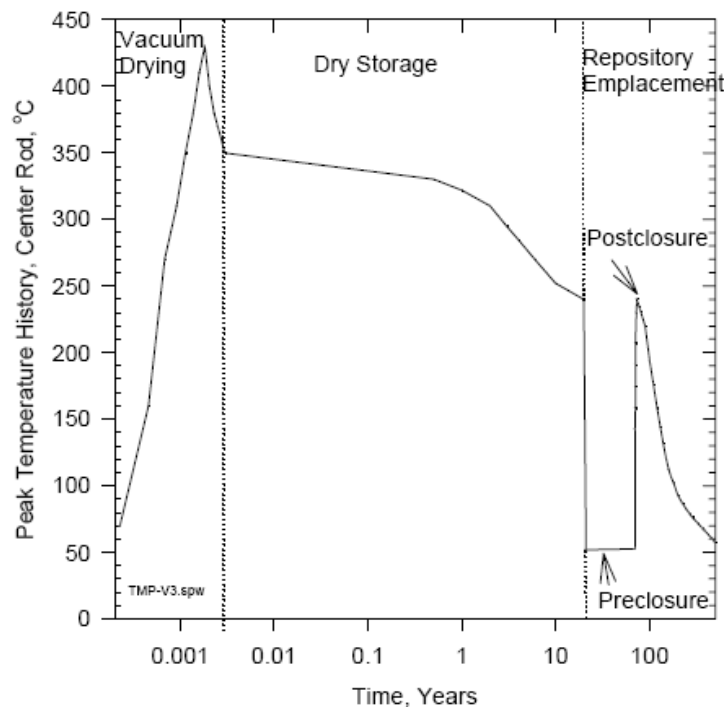


Fig. 1: Temperature vs. time during dry storage for Yucca Mountain with repository emplacement after 10 years of dry storage [4].

The objective of this study was firstly to explore the limitations of the present creep models in TRANSURANUS for long term creep processes under dry storage conditions. If the creep models were found to be inappropriate

then next objective was to formulate the properties of an “ideal” creep model for dry storage. The creep models implemented in TRANSURANUS will be compared with creep tests by Spilker et al. [5] on unirradiated Zircaloy cladding tubes.

Spilker et al. carried out creep tests to support licensing of the transport and storage cask CASTOR V for dry storage of light water reactor (LWR) fuel rods after extended burnup of approximately 55 GWd/tHM. Licensing of dry storage casks requires that spent LWR fuel claddings do not fail during storage. The leading failure mechanism for LWR fuel with Zircaloy cladding under normal long-term dry storage conditions is creep due to internal fission gas overpressure. The most common design rule is that the creep strain of the cladding should not exceed 1 % during dry storage, which is generally considered a conservative criterion for cladding failure. Irradiation induces material hardening which lowers the creep rate. Post-pile creep of irradiated Zircaloy cladding can therefore be conservatively be described by creep of unirradiated material.

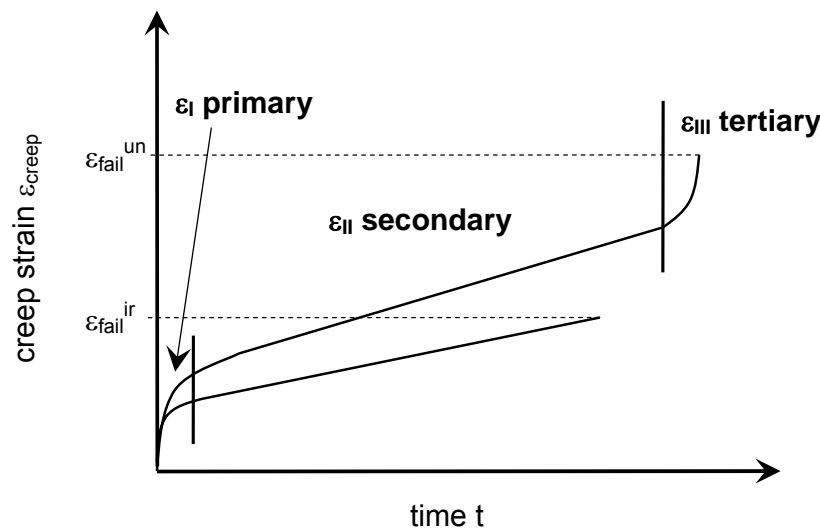


Fig. 2: Typical creep strain vs. time curves for irradiated and unirradiated material

Figure 2 shows typical thermal creep strain versus time under constant load for unirradiated and irradiated materials respectively. Such thermal creep needs to be taken into account when the temperature is between 30% and 70% of the material's melting temperature in Kelvin. Zircaloys have a melting temperature of about 2100 K (~1800 °C) and 30% of this corresponds to about 350°C. The longer the times we need to consider the lower cut-off temperature. Thus for long-term storage, where hundred years or more may need to be assessed, temperatures as low as 200°C (22% of the melting temperature) may need to be considered.

The creep curve can be separated into three distinct regimes: primary creep, in which the materials appear to harden so the creep rate diminishes; the secondary creep, in which the hardening and softening mechanisms appear to balance to produce a constant creep rate; and the tertiary creep in which the material softens until creep rupture occurs. The secondary creep is the most important regime both in terms of time and accumulated strain and often the only one considered in an engineering assessment. The tertiary strain constitutes generally a very short time. The primary creep corresponds to a small fraction of the total creep but the primary creep contributes more to the total strain at lower temperatures.

The total strain consists of a static component (elastic with possible plastic contribution if the load is high enough), a thermal component and the creep component.

$$\varepsilon_{tot} = \varepsilon_{static} + \varepsilon_{thermal} + \varepsilon_{creep} \quad (1)$$

The creep strain can be calculated by integrating the strain rates of the three stages $\dot{\varepsilon}_I, \dot{\varepsilon}_{II}, \dot{\varepsilon}_{III}$ over time t:

$$\varepsilon_{creep}(t) = \int_0^t [\dot{\varepsilon}_I(t) + \dot{\varepsilon}_{II}(t) + \dot{\varepsilon}_{III}(t)] dt. \quad (2)$$

The extent to which the different stages are developed depends strongly on the applied load and the temperature but also on the microstructure. Irradiation has two main effects as illustrated in Figure 2: the creep rate is lower, typically by a factor 2 [5] due to irradiation induced hardening, but more importantly the failure strain may be lowered by one order of magnitude or more [2] and failure may occur without any tertiary creep.

Primary creep is often described by functions such as [6]

$$\dot{\varepsilon}_I(t) = K(T) \sigma^m t^n \quad \text{with} \quad n < 1, \quad (3)$$

or [7]

$$\dot{\varepsilon}_I(t) = L(T) \sigma^m \varepsilon^{-p} \quad (4)$$

where K, m, n, L and p are material parameters. The mechanism for primary creep is the climb of dislocations that are not pinned in a matrix. The number of dislocations increases with the strain and the material hardens as dislocations impede. This is the transition between primary and secondary creep. The primary creep of a material is due to the number of dislocations initially present. It therefore depends strongly on the history of the material. It also depends on the temperature but to a much lesser extent than for the secondary creep. The primary creep is often a very small part of the total strain and therefore can often be neglected. It is generally more important for "low-temperature creep" for temperatures in the range of 20 to 40 % of the melting temperature of the material involved.

The secondary or steady state creep is characterized by a constant strain rate. The most commonly used model to describe secondary creep is the Norton creep law:

$$\dot{\varepsilon}_{II}(t) = A(T) \cdot \left(\frac{\sigma}{\sigma_0} \right)^m \cdot e^{-\frac{\Delta E}{kT}} \quad (5)$$

where k is the Boltzmann constant, ΔE the excitation energy and A, σ_0 and m are material parameters. The parameter A increased with the ratio between the grain size and the Burger's vector (d/b) and is often inversely proportional to the temperature. The secondary creep is also a dislocation climb mechanism but where dislocation jogs impede the movement of dislocations. It is normally the dominant mechanism for temperatures between 30 to 70 % of the melting temperature. At temperatures above 70 % of the melting temperature the creep mechanism is diffusion of atoms (Coble or Nabarro-Herring creep). The formula in that case is similar to the Norton law but with m=1.

A very important aspect of creep under long-term storage is that the dominant creep mechanism may change as the temperature drops with time. This is illustrated by deformation mechanisms maps as Figure 3, which shows the creep mechanisms for nickel in dependence of stress and temperature. The mechanisms are also affected by irradiation.

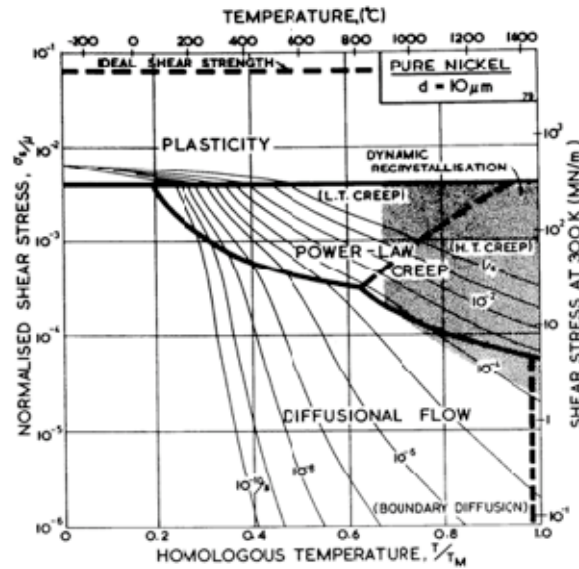


Fig. 3: Creep mechanisms of nickel in dependence of stress and temperature

2 The experimental program

Spilker et al. [5] carried out a creep investigation program for six different zircaloy claddings. These claddings were part of high corrosion resistance claddings under development but no details were provided [5]. The cladding types differed slightly with respect to outer diameter. Each specimen for the creep tests was manufactured as closed pressurized test samples with Helium as filling gas. The length of the samples was 10 times the rod diameter. The main type of cladding, referred as test type I, had a nominal outer diameter of 10.75 mm and 0.73 mm wall thickness. For a thin walled tube ($t/D \ll 1$) the stresses are directly determined from equilibrium and the hoop stress and axial stress are given by

$$\sigma_{\varphi} = \frac{D}{2t} p, \sigma_z = \frac{D}{4t} p, \quad (6)$$

where D and t are the diameter and wall thickness respectively.

This cladding type was tested for hoop stresses 80, 100, 120 and 150 MPa at the temperatures 250, 300, 350, 375 and 400°C. The duration of each test was 10000 hours (which corresponds to 13 months) with intermediate measurements performed after 240, 400, 800, 1500, 3000, 5000 and 10000 hours. Five other types of cladding referred to as II to VI were tested additionally for the hoop stresses 80, 100, 120 and 150 MPa at 375°C only. Table 1 summarizes the test programme.

Table 1: The test program

Cladding type	Outer diameter [mm]	Wall thickness [mm]	Temperature [°C]	Hoop stresses [MPa]			
I	10.75	0.73	250	80	100	120	150
			300	80	100	120	150
			350	80	100	120	150
			375	80	100	120	150
			400	80	100	120	150
II	12.26		375	80	100	120	150
III	11.20		375	80	100	120	150
IV	11.64		375	80	100	120	150
V	9.60		375	80	100	120	150
VI	9.62		375	80	100	120	150

3 The simulation model

TRANSURANUS [1] is a one-dimensional code for the mechanical and thermal analysis of fuel rods and accounts for most physical effects related to nuclear fission such as fission gas release and neutron capture.

3.1 Geometry of the model

Figure 4 shows the discretization of the simulation model. We assume that there is no axial variation and there is therefore only one element. In the radial direction the tube is modeled with five elements.

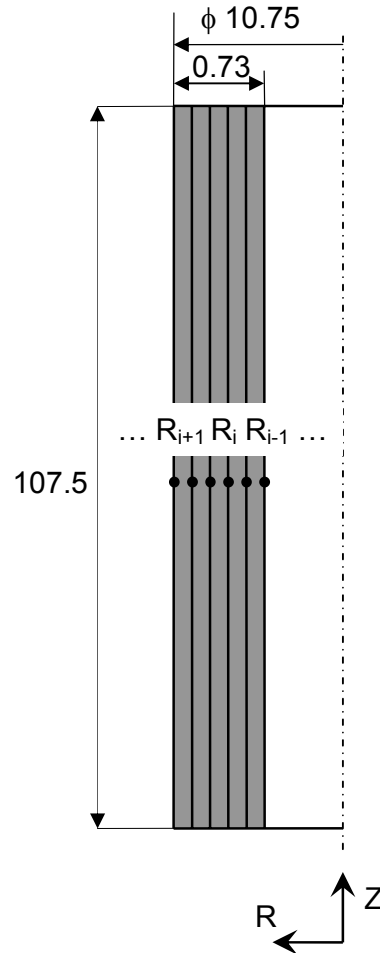


Fig. 4: Geometry of TRANSURANUS model

3.2 Thermal and mechanical loads

Table 2 lists the most relevant parameters for the TRANSURANUS input file (for a complete description of all the input parameters refer to [1]). These input parameters are all related to temperature, pressure and the media surrounding the cladding and are self-explanatory.

Table 2: Relevant TRANSURANUS input parameters

Input parameter	Parameter name	Value
Helium fill gas concentration	CANF(1)	1.0
Other fill gas concentrations	CANF(i), i=2-10	0.0
Cooling media of cladding	MPgen_cool	5 (= Helium)
Fill gas temperature	Ti0ein	According temperature values Table 1
Coolant temperature	IWERT(9)	According temperature values Table 1
Fixed coolant temperature?	IKUEHL	1 (= yes)
Heat transfer coefficient cladding -- coolant	IALPHA	2 (= infinity)
Initial fill gas pressure	Pi0ein	According hoop stress values Table 1

3.3 Creep models and material properties

3.3.1 The creep model of Laßmann and Moreno

The creep model of Laßmann and Moreno (L-M) [8] is the standard model in TRANSURANUS to simulate creep of Zircaloy-2 and Zircaloy-4 fuel cladding in reactor operation. As mentioned above the temperature in the core of a typical PWR lies around 350-400°C, which is a temperature range where secondary creep is expected to be the dominant creep mechanism. As a result the creep model of Laßmann and Moreno does not account for primary creep and it is therefore only of limited use for dry storage conditions for lower temperatures. In the Laßmann-Moreno model the creep rate has two parts, a mechanical-thermal part, which depends entirely upon the temperature and stress involved, and a part related to the level of irradiation, which depends entirely upon the stress and the neutron flux:

$$\dot{\epsilon}_{ILLM} = \dot{\epsilon}_{mth} + \dot{\epsilon}_{nflux} \quad (7)$$

The mechanical-thermal part $\dot{\epsilon}_{mth}$ [1/h] is defined as

$$\dot{\epsilon}_{mth} = 1.083 \cdot 10^5 \cdot \exp\left(-\frac{17000}{T}\right) \cdot \sinh\left(\frac{\sigma}{60}\right), \quad (8)$$

with the temperature T [K] and the stress σ [MPa]. The part related to the irradiation $\dot{\epsilon}_{nflux}$ is proportional to the neutron flux and not relevant for the unirradiated tests by Spilker et al. [8]. By comparing equation (8) with equation (5) it follows that the creep model of Laßmann and Moreno is similar to Norton's creep model but where the material parameter A is temperature independent and the sinh function has replaced the power law for the stress dependence. This suggests that this model should only be used in a relatively narrow temperature range to which it is calibrated.

3.3.2 The creep model of Mayuzumi and Onchi

The L-M model is mainly intended for fuel rods in normal reactor operation. Mayuzumi and Onchi have proposed a creep model which covers a wider temperature range to be used under long-term storage conditions. It is based on a general form for empirical creep models (see [7]):

$$\varepsilon_{MO} = \varepsilon_t + \dot{\varepsilon}_s t \quad (9)$$

The steady-state part $\dot{\varepsilon}_s$ [1/s] depends upon the applied stress σ [MPa] and the temperature T [K] and when calibrated to their data it takes the form [9,10]:

$$\dot{\varepsilon}_s = 7.26 \cdot 10^4 \frac{E}{T} \cdot \exp\left(2320 \frac{\sigma}{E}\right) \cdot \exp\left(-\frac{215000}{R \cdot T}\right), \quad (10)$$

with the E-Modulus E [MPa] and the universal gas constant $R=8.314$ J/mol/K. The part ε_t , which Mayuzumi and Onchi refer to as the transient part and corresponds to the primary creep, is defined by [9,10]:

$$\varepsilon_t = \varepsilon_t^s \left[1 - \exp\left\{-D \cdot (\dot{\varepsilon}_s t)^{0.63}\right\} \right], \quad (11)$$

with

$$\varepsilon_t^s = \exp[-0.0866T + 64.1] \cdot (\dot{\varepsilon}_s)^{-0.00336T + 2.81}, \quad (12)$$

$$D = 9.28 \cdot 10^7 \cdot \exp(-0.0212T). \quad (13)$$

The M-O model and L-M differ with respect to the stress function but more important is that the M-O model also has a temperature dependence in the denominator in addition to the Arrhenius function. In TRANSURANUS only the secondary creep part of the M-O model was implemented at this stage due to solver related reasons. In order to assess the primary creep contribution we have implemented the complete M-O model as MATLAB routines.

For the E-Modulus Mayuzumi and Onchi assume that the E-Modulus is linearly dependent from the temperature in the following way [9]:

$$E = 1.148 \cdot 10^5 - 59.9 \cdot T. \quad (14)$$

This temperature dependence of the E-Modulus is also used for the implementation of the creep model of Mayuzumi and Onchi in TRANSURANUS. For all other temperature dependent material models for Zircaloy in TRANSURANUS including the Laßmann-Moreno creep model the following slightly different definition is used [8]:

$$E = 10^5 - 59 \cdot T \quad (15)$$

For the Poisson's ratio a unique and temperature independent value of $\nu=0.325$ is used.

The M-O creep model in the form above is intended for temperatures between 353 and 420°C and hoop stresses of 55 to 125 MPa [9]. Thus it does not cover the whole temperature range of interest for dry storage of spent nuclear fuel or accident conditions. Mayuzumi and Onchi have also calibrated their creep model for higher temperatures relevant for accident conditions [11], like e.g. fire near the spent nuclear fuel storage cask.

4 Comparison of experimental and computed results

4.1 Comparison for 250°C

Figure 5 shows the measured and computed creep strain vs time for an initial hoop stress of 80 MPa. Figure 5a shows the measured creep strains along with the creep strains of the TRANSURANUS simulations with both described creep models. In Figure 5b the creep strain from the L-M creep model is replaced by the total creep strain from the M-O model as implemented in MATLAB. The corresponding results at hoop stress of 150 MPa are shown in Figure 6a and b) respectively. First of all it can be noted that the measured creep strain is below 0.2%, which is quite a small value and the secondary creep is not attained. The two creep models predict essentially no creep strain for the two stress levels.

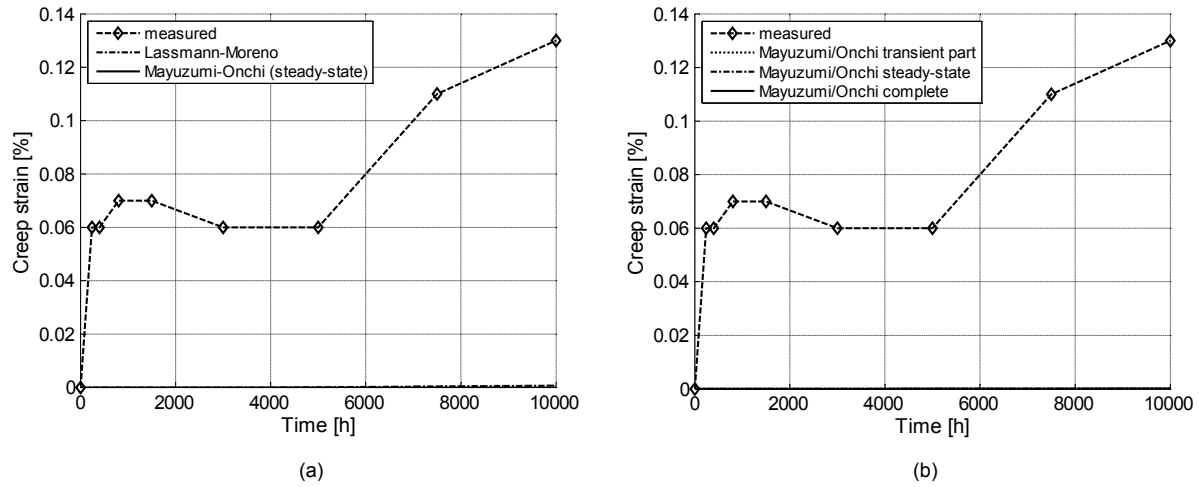


Fig. 5: Comparison creep strain vs time for $T = 250^{\circ}\text{C}$ and $\sigma_0 = 80 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

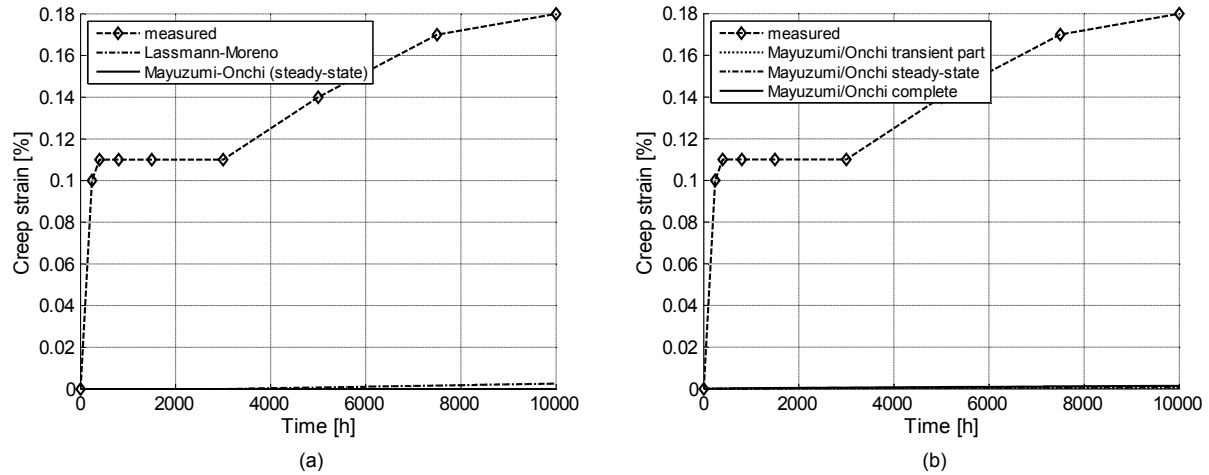


Fig. 6: Comparison creep strain vs time for $T = 250^{\circ}\text{C}$ and $\sigma_0 = 150 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

4.2 Comparison for 300°C

The Figures 7 and 8 depict the computed and measured creep strains vs time at 300°C for the initial hoop stresses 80 MPa and 150 MPa respectively. The measured creep strains indicate that steady-state creep regime has been attained after 4000 hours. It can also be noted that the primary strains for both temperatures are about 0.1% and 0.2% for 80 and 150 MPa respectively. The computed creep strains are still significantly lower than the measured ones. This applies to both the primary and secondary creep strain. It should be remembered that both 250°C and 300°C are well below the temperature range for which the models have been calibrated.

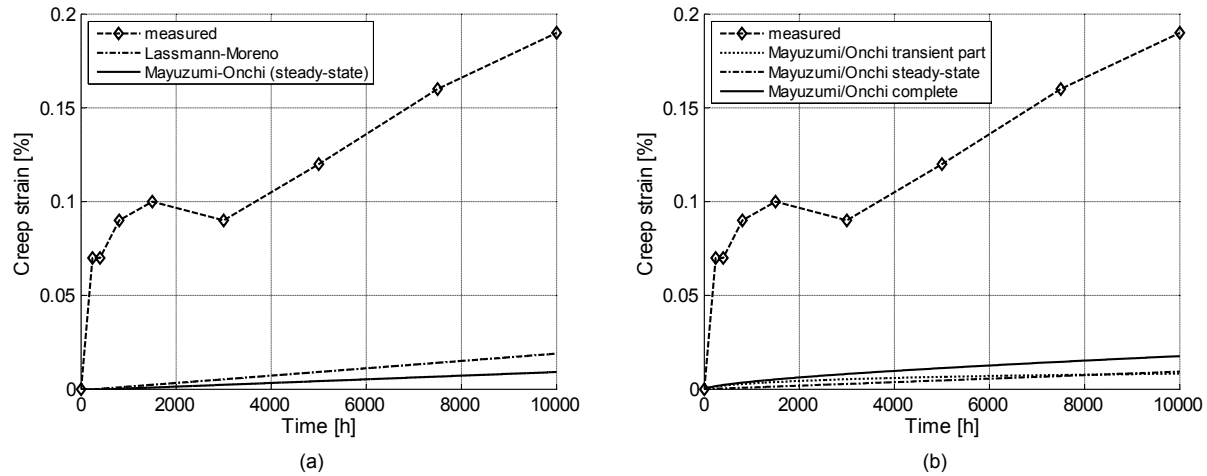


Fig. 7: Comparison creep strain vs time for $T = 300^{\circ}\text{C}$ and $\sigma_0 = 80 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

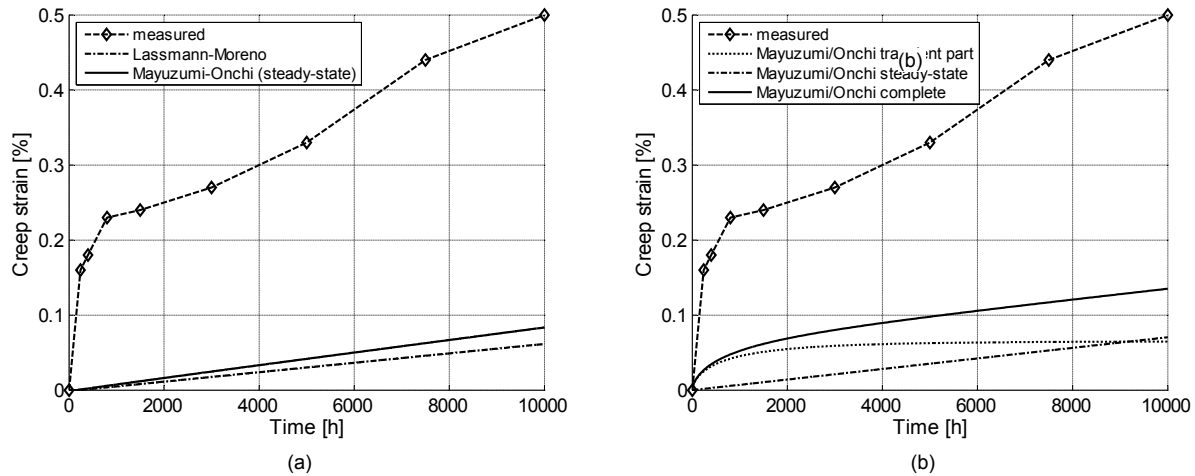


Fig. 8: Comparison creep strain vs time for $T = 300^{\circ}\text{C}$ and $\sigma_0 = 150 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

4.3 Comparison for 350°C

The Figures 9 to 12 show the computed and measured hoop strains vs time for 350°C for the nominal hoop stresses 80, 100, 120 and 150 MPa respectively. The tests indicate that primary creep is dominant for the first 2000-3000 hours when the initial hoop stresses are in the range 80-120 MPa and then followed by a secondary creep. For 150 MPa there seems to be primary creep for the entire test duration.

The computed creep strain for the M-O model is smaller than the measured strain for the nominal stress levels 80, 100 and 120 MPa but the difference gets smaller with increasing load and at 150 MPa the M-O model with primary and secondary creep has in fact higher strain beyond 6000 hours. The primary and secondary creep in the tests have roughly the same magnitude after 10 000 hours. The L-M model severely underestimates the creep strain and this trend increases with increasing load.

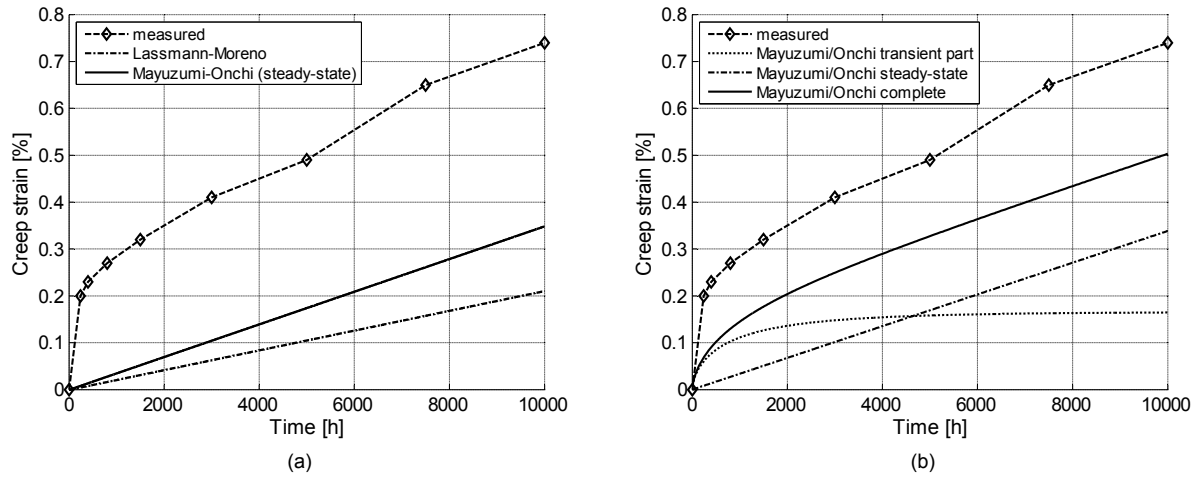


Fig. 9: Comparison creep strain vs time for $T = 350^{\circ}\text{C}$ and $\sigma_0 = 80 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

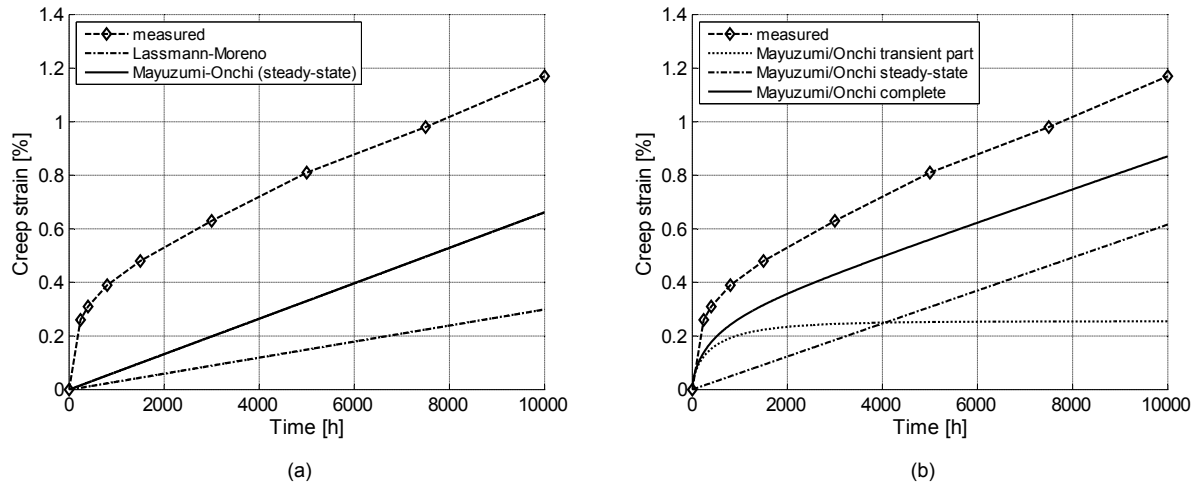


Fig. 10: Comparison creep strain vs time for $T = 350^{\circ}\text{C}$ and $\sigma_0 = 100 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

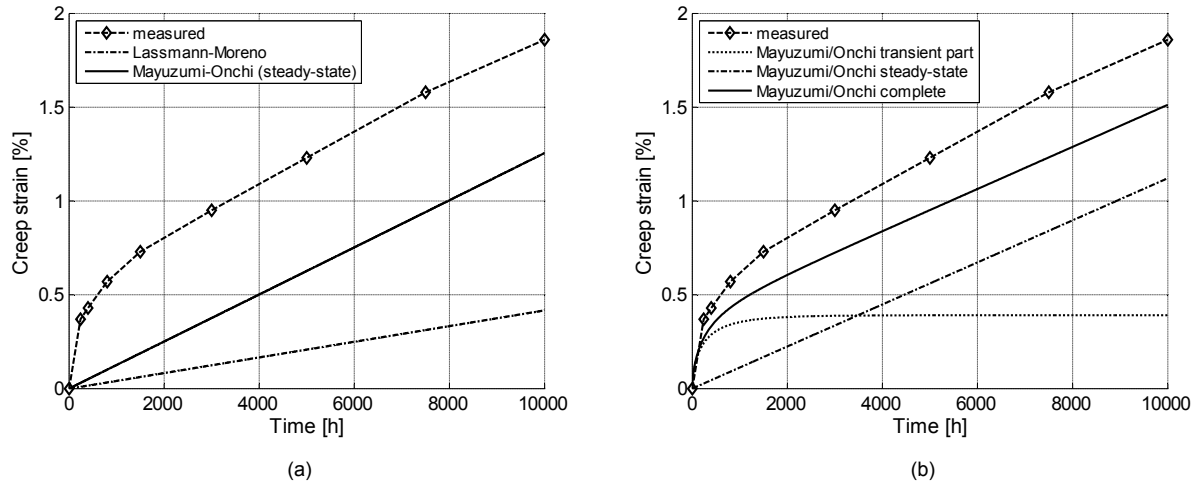


Fig. 11: Comparison creep strain vs time for $T = 350^{\circ}\text{C}$ and $\sigma_0 = 120 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

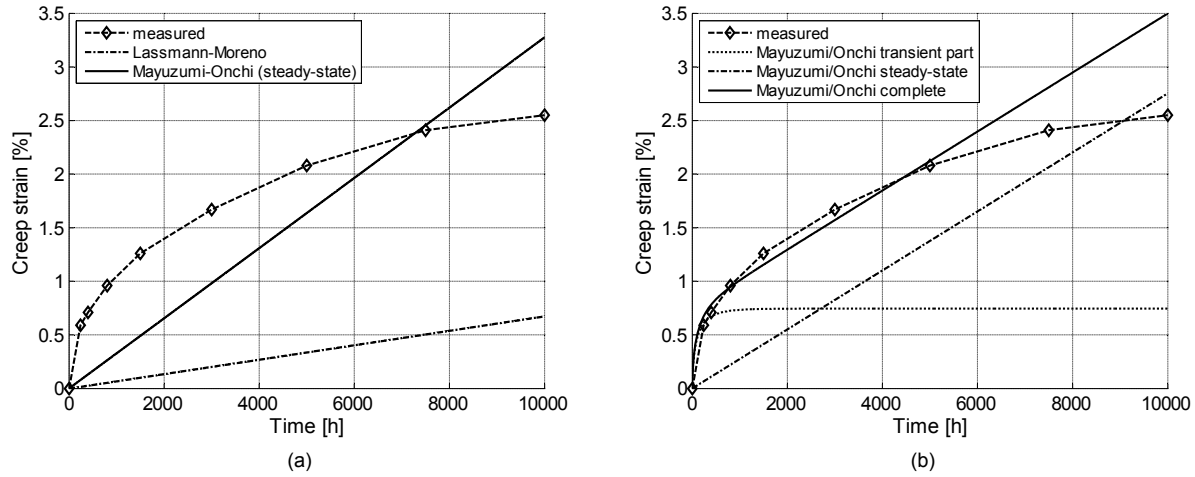


Fig. 12: Comparison creep strain vs time for $T = 350^{\circ}\text{C}$ and $\sigma_0 = 150 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

4.4 Comparison for 375°C

For 375°C the curves for the measured creep strains show a distinct steady-state creep after 2000 hours for all the four nominal hoop stresses involved as Figures 13, 14, 15 and 16 indicate. As for 350°C , the L-M predicts consistently lower creep strains than in the tests. The M-O model with primary and secondary strain components consistently underestimates the creep strain. In contrast to 350°C the relative difference is relatively independent of the load level.

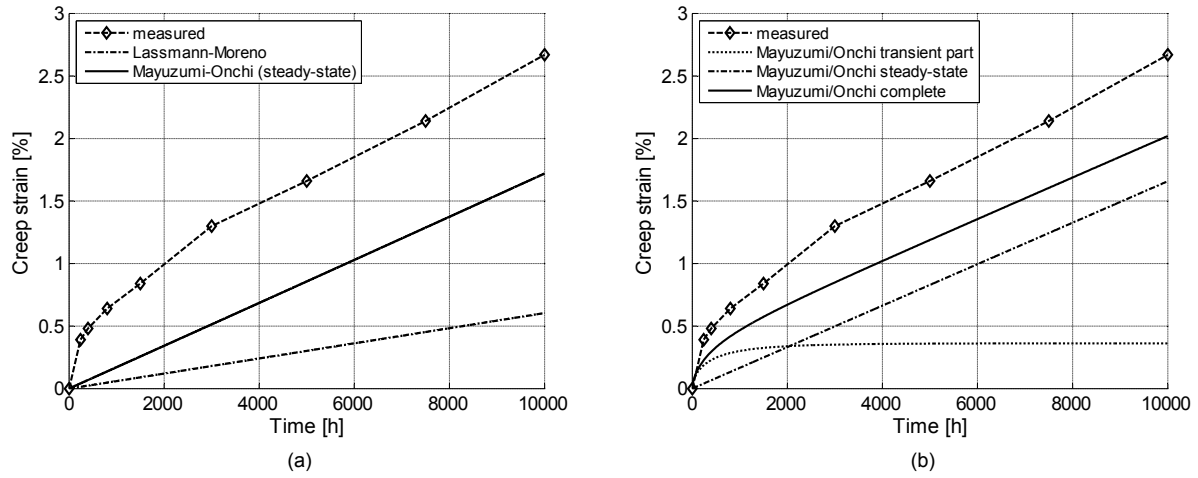


Fig. 13: Comparison creep strain vs time for $T = 375^{\circ}\text{C}$ and $\sigma_0 = 80 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

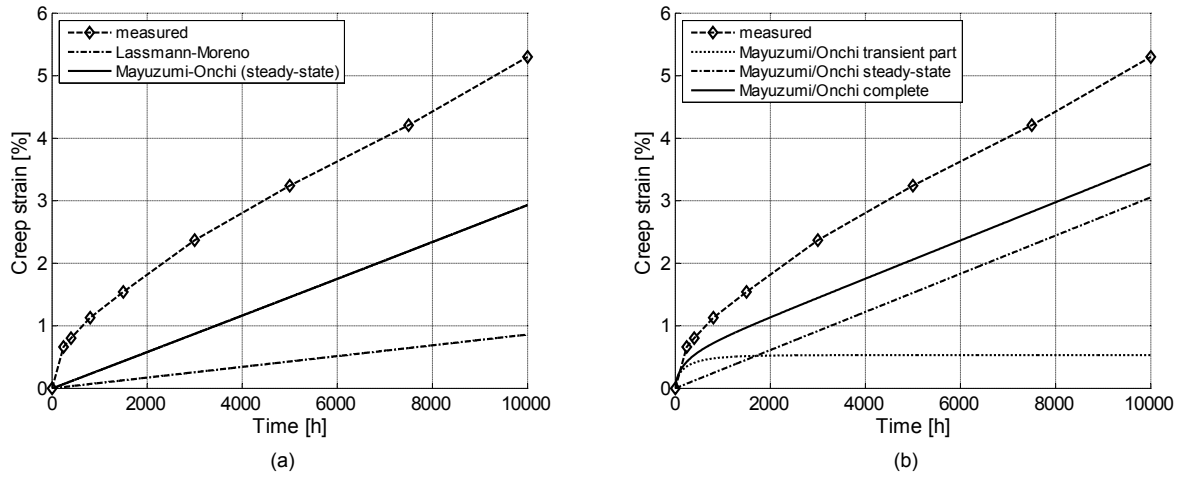


Fig. 14: Comparison creep strain vs time for $T = 375^{\circ}\text{C}$ and $\sigma_0 = 100 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

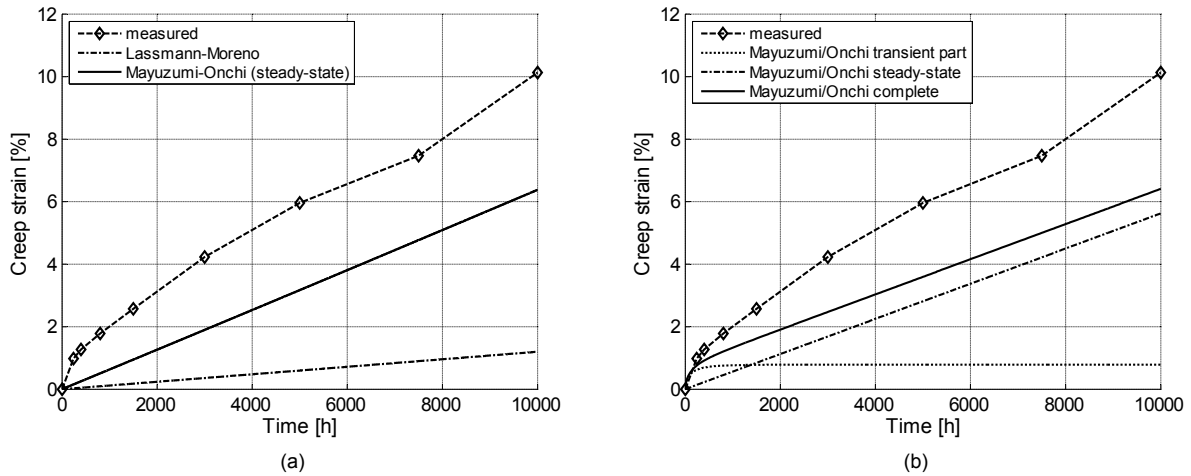


Fig. 15: Comparison creep strain vs time for $T = 375^{\circ}\text{C}$ and $\sigma_0 = 120 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

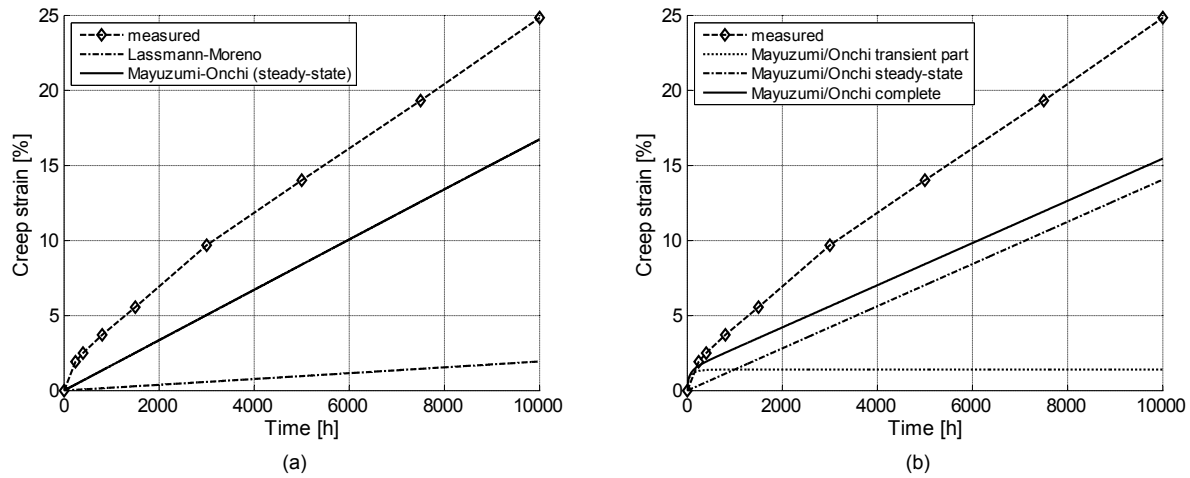


Fig. 16: Comparison creep strain vs time for $T = 375^{\circ}\text{C}$ and $\sigma_0 = 150 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

4.5 Comparison for 400°C

At 400°C measured deformations are completely dominated by steady-state creep. The primary creep is only active for the first 1000 h and represents only a very small fraction of the total creep strain. At 150 MPa the tests show signs of tertiary creep. The strains predicted by the M-O model agree quite well with the measured data. This is not unexpected since 400°C is within the temperature range for which the creep model was calibrated. The L-M severely underestimates the creep strains.

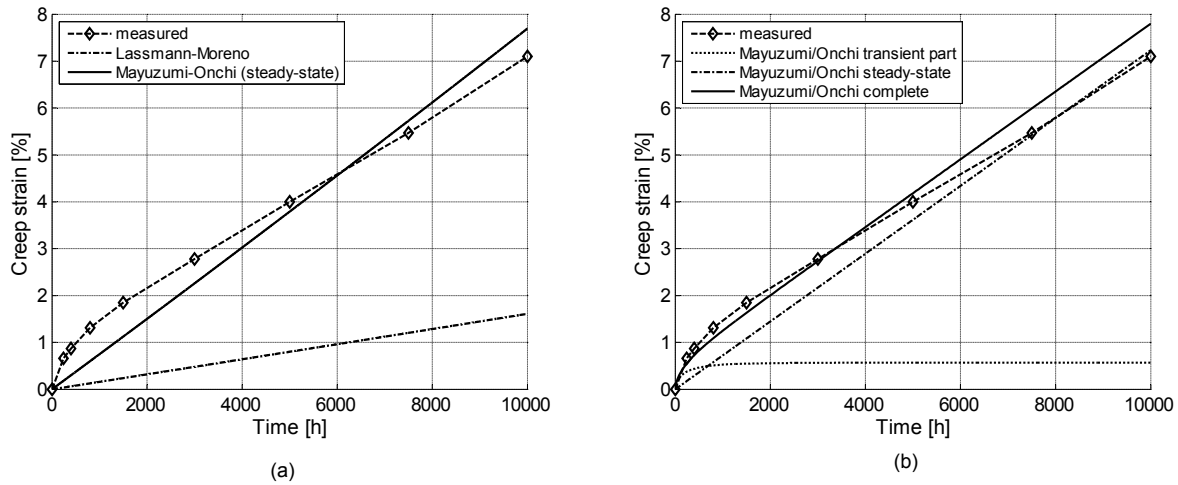


Fig. 17: Comparison creep strain vs time for $T = 400^{\circ}\text{C}$ and $\sigma_0 = 80 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

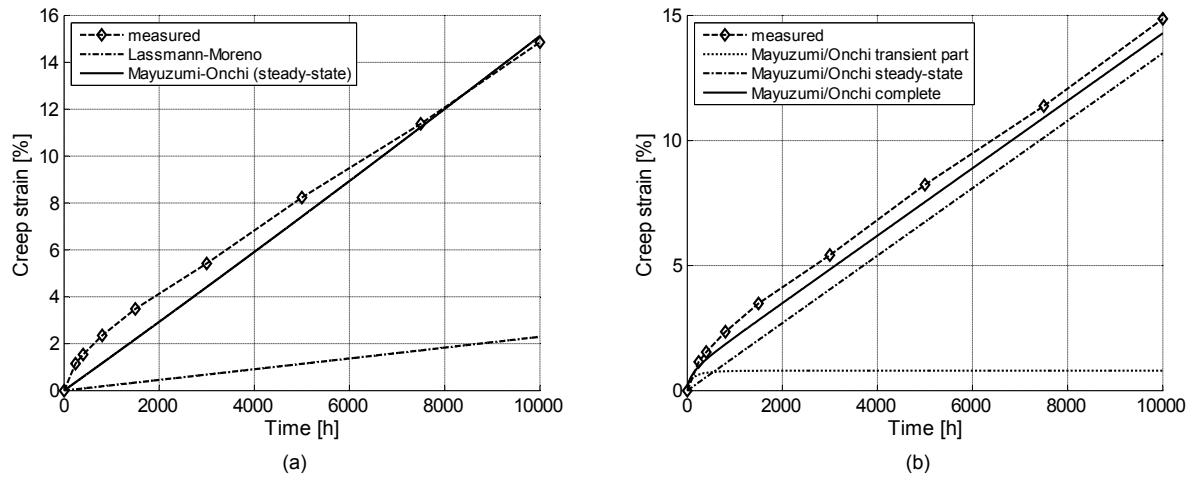


Fig. 18: Comparison creep strain vs time for $T = 400^{\circ}\text{C}$ and $\sigma_0 = 100 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

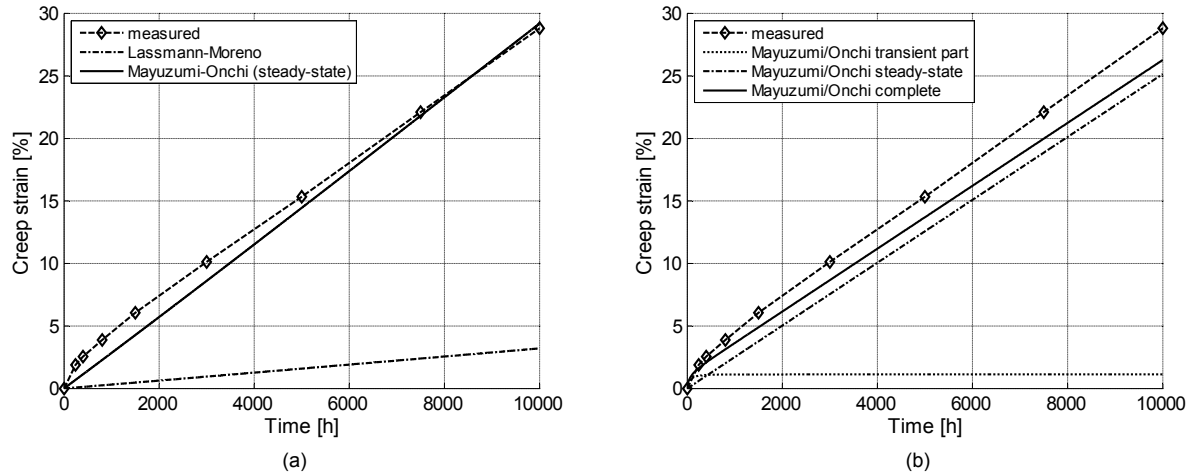


Fig. 19: Comparison creep strain vs time for $T = 400^{\circ}\text{C}$ and $\sigma_0 = 120 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

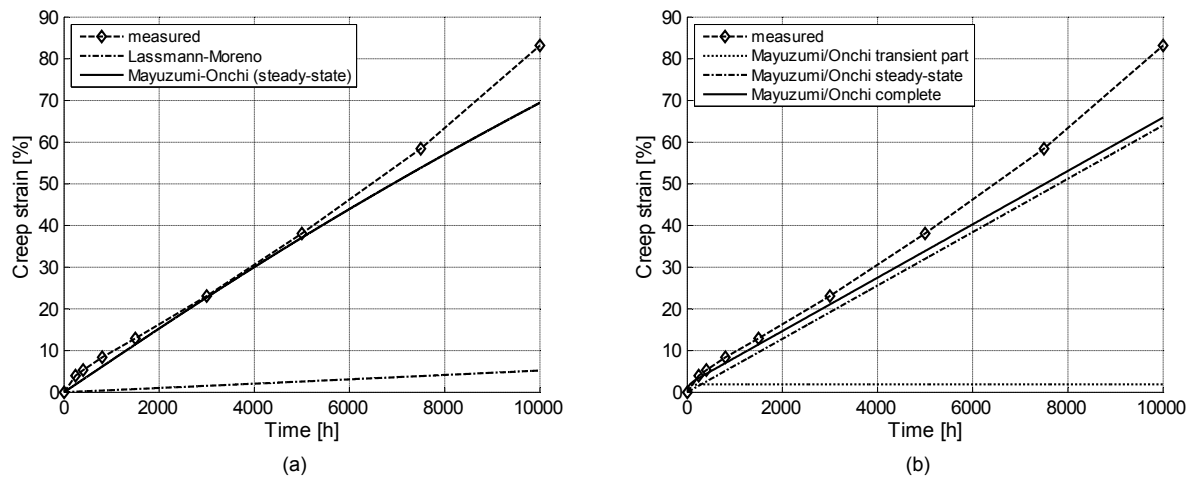


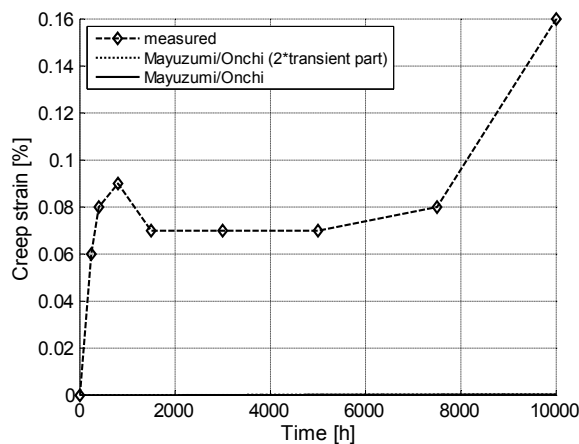
Fig. 20: Comparison creep strain vs time for $T = 400^{\circ}\text{C}$ and $\sigma_0 = 150 \text{ MPa}$ for measurements with (a) Laßmann-Moreno and Mayuzumi-Onchi (steady-state) and (b) Mayuzumi-Onchi (single parts & complete)

5 Discussion

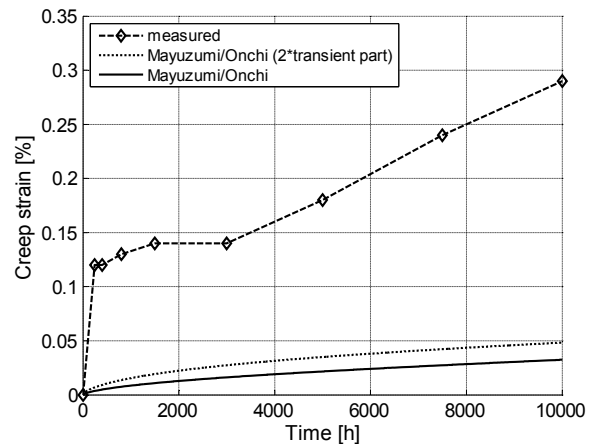
Unirradiated cladding tubes have quite large creep ductility. In Figure 20 we see that strains as high as 80% were sustained without cladding failure. The failure strain will be significantly lower for irradiated claddings. A 1% strain criterion should normally provide a sufficient safety margin but as reported by for instance Ferry et al. [2], for specimens with high levels of radial hydrides failure may occur for strains below 1%. From the measured strains we conclude that primary creep cannot be neglected for strain levels of 1%. Hence a creep model for long-term storage should include primary creep. The creep rate depends strongly on the temperature. For 250°C, the measured creep strains are only 0.2% after 10 000 (which corresponds to about one year), but since steady-state creep has not been attained one cannot rule out that 1% strain could not be attained for extended periods at this temperature.

The L-M model, which is the standard model implemented in TRANSURANUS severely underestimated the creep strains for all temperatures and stress levels. The L-M does not allow for primary creep and it has only temperature dependence through the exponential Arrhenius relation. It should however be possible to get good agreement at least for one temperature if properly calibrated. In TRANSURANUS we used pre-set values for the three parameters which apparently were not well calibrated for this material.

The M-O model gave results that agreed reasonably well with the measured creep strains for temperatures above between 350°C and 400°C. The main discrepancy was that the primary creep strain was underestimated. The model parameters were taken directly from [10,11] which comes from a material that is different from the ones in Spilker's test. The model would work better had the data been calibrated for the actual material. Figure 21 illustrates the model gives better agreement if the primary creep is increased by a factor 2.



a)



b)

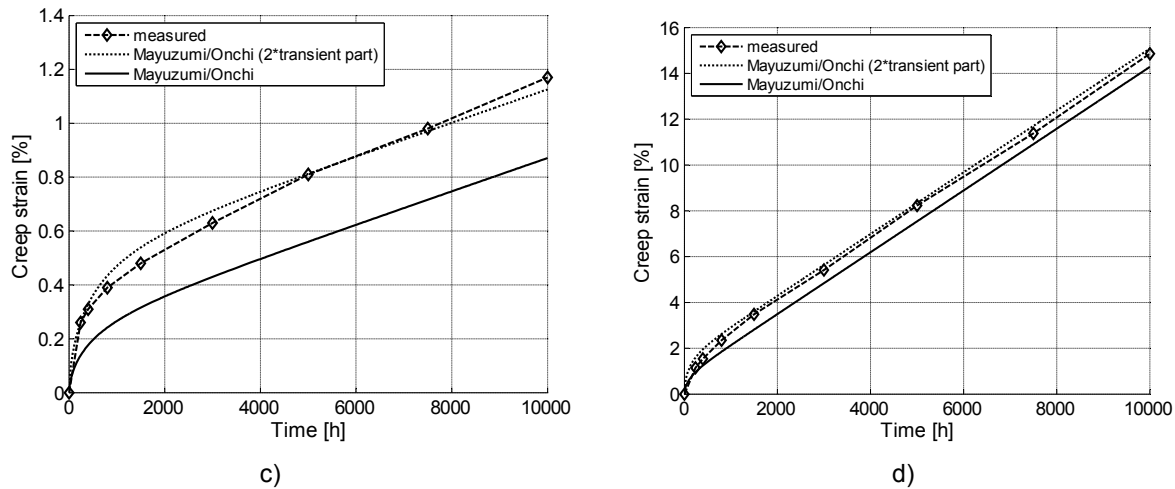


Figure 21 The measured and computed creep strain using the standard M-O model and with the primary creep with a factor 2 a) 250°C b) 300°C c) 350°C d) 400°C

The agreement is quite good for 350°C and 400°C but for the lower temperatures the creep strains are still underestimated. This suggests that the M-O model can be quite accurate for the higher temperatures if properly calibrated, and if it can be demonstrated that the long term creep is negligible for temperatures below 300°C then it would be sufficient. If we would like to model lower temperatures then the models would need to be developed further. One possibility is to calibrate the models to different temperature ranges but that would not be an ideal solution since the creep mechanism probably changes. Deformation mechanism maps for the zircalloys would be a very useful tool to support models that account for a change in creep mechanism. Better understanding of the creep mechanism would also be a prerequisite to develop models that account for the irradiation effects.

6 Conclusions

The creep under long-term storage conditions occurs under a relatively wide temperature range (400°C - 200°C). In this temperature range primary creep is important and should be accounted for.

- The Laßmann and Moreno as implemented in TRANSURANUS underestimates severely the creep strain.
- The Mayuzumi and Onchi model gives a reasonable agreement with measured data for the unirradiated claddings. The agreement could be improved if the model were calibrated to the specific material data. The contribution of the accumulated creep when the temperature is below 300°C is probably rather small even if the durations are quite long. Hence good prediction of the strains for temperatures above 300°C using data for unirradiated material should provide sufficient safety margins for long-term creep under storage conditions with irradiated material.
- Accurate predictions under low-temperature conditions and for irradiated materials would require methods that account for the shift in creep mechanisms. This would of course be a very challenging research task.

7 References

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- [11] Mayuzumi M. and Onchi T.: *Creep deformation and rupture properties of unirradiated Zircaloy-4 nuclear fuel cladding tube at temperatures of 727 to 857 K*, Journal of Nuclear Materials, Vol. 175, 1990, p. 135-142

Appendix – Example TRANSURANUS input file

```

*****
*
* TRANSURANUS Standard Input Format
*
* Input file to simulate measured hoop strains of the creep tests by Spilker et al.
* for T=400degC and initial hoop strain sigma=150MPa
*
*****
* KANF(=IDEN)      Identification for beginning of data set
* INTRUP           Restart Option
*
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+
IDEN0
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format: A4,I1
*
*****
*
* NKOMM           Number of input text records incl. specification of output files
* PINCHA (1)      Reactor
* PINCHA (2)      Flux
* PINCHA (3)      Fuel Material
* PINCHA (4)      Clad Material
*
* nkomm   pincha(1) pincha(2) pincha(3) pincha(4)
*+-----+-----+-----+-----+-----+-----+-----+-----+-----+
9          LWR          THE          OXI          ZIR
*+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:I2,8X,4(A3,7X)
*
*****
*
* Input text records the last 5 of which contain specification of output files
*
* ITEXTK(NKOMM-4) Statistic File
* ITEXTK(NKOMM-3) Plot Information File
* ITEXTK(NKOMM-2) Micro Step File
* ITEXTK(NKOMM-1) Macro Step File
* ITEXTK(NKOMM)   Restart File
*
*-----+-----+
Verification of the test results in article by Spilker et al.
      Test to simulate Zircaloy cladding under dry storage conditions
      Main degradation mechanism: creep
      Temperatures and inner pressures are given
spilker_400d150MPa.sta
spilker_400d150MPa.pli
spilker_400d150MPa.mic
spilker_400d150MPa.mac
spilker_400d150MPa.res
*-----+-----+
* format: A80
*
*****
*
* m3      fgrmod   ixmode   ModProp   istati   ibmech   izenka   ioxire
*      itheoc   ikuehl   iDifSolv   ModAx   idensi   ialpha   insta   kplot
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+
1      1      0      1      2      0      2      0      0      0      0      2      0      2      0      1
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:16I5
*
*****
*
* ihgap   istruk   ikueka   ibloc   ireloc   iria   ihbs   icrkpi
*      intaxl   irand   itemte   ModStr   nfront   igd   ifba   kokoko
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+
0      0      0      0      2      0      0      0      0      0      0      0      0      1      0
*--+-----+-----+-----+-----+-----+-----+-----+-----+-----+

```

```
* format:16I5
*
*****
*
* islice      ipure      isurfb      istzne      iplnum      igrbdm      itLog
*             ihydd       ipoint       igrnsz       icorro       inoise       iHe        iclfail
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
*   1         0         0         0         0         1         0         0         0         0         0         0         0         0
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:11I5
*
*****
*
* iphaseZr    ioxide
*              iLoca
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
*   1         0         0
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:11I5
*
*****
*
* Options for general material properties
*
* MPgen_cool
* MPgen_clad
*   MPgen_fuel(1)
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* 52020
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:40I2
*
*****
*
* Options for specific material properties (cladding)
*
* ModClad(1:20)
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* 0 0 0 0 0 0 6 0 0 0 0 0 0 0 0 0 0 0 0 0
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:20I3
*
* Options for specific material properties (fuel)
*
* ModFuel(1:20)
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* 18 0 0 0 13 21 18 30 30 18 18 0 0 0 0 0 0 0 0 0
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:20I3
*
* Options for specific material properties (coolant)
*
* ModCool(1:10)
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* 18 0 0 0 13 21 18 30 30 18
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:10I3
*
*****
*
* BETA    Axial anisotropy factor for densification
*
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* 0.
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:F10.5
*
*****
*
* TTRANS   Time at which transient starts [h]
* DTMAX    Maximum time step length [h]
* DT000    Length of the first time step as prescribed by the user
* DBLIND    Blind variable
```

```

*
* ttrans          dtmax          dt000          dblind
*-----+-----+-----+-----+-----+
* 0.              1.e+00          1.e-15          1.
*-----+-----+-----+-----+
* format:4D20.13
*
*****
*
* ETACRP Maximum creep rate (standard value) [1/h]
* nCracks Number of cracks in the fuel
* Gas_Gb Saturation limit for grain boundary gas [umol/mm**2]
*
*-----+-----+-----+-----+
* 0.1e-04          0.              0.
*-----+-----+-----+
* format:E10.3
*
*****
*
* Auxiliary variables used for model development
*
* iiii(1:5) rrrr(1)  rrrr(2)  rrrr(3)  rrrr(4)  rrrr(5)
*+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
* 0 0 0 0 0  0.0      0.0      0.0      0.0      0.0
*+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
* format:5I2,5E10.3
*
*****
*
* FMUEH Friction coefficient between fuel and cladding: static friction
* FMUEF Friction coefficient between fuel and cladding: sliding friction
* RSNTRO Maximum density change determined by a resintering test of 24 h
* TSINT0 Input sintering temperature of the fuel [C]
* COLDWO Cold work (fraction of cross-sectional area reduction)
*
* Texture factors for cladding irradiation growth:
* FTXRAD Radial
* FTXTAN Tangential
* FTXAXI Axial
*
* fmueh  fmuef  rsntro  tsint0  coldwo  FtxRad  FtxTan  FtxAxi
*-----+-----+-----+-----+-----+-----+-----+-----+
* 0.8      0.8              -999.      -999.      -999.
*-----+-----+-----+-----+-----+-----+-----+
* format:8F10.5
*
*****
*
* T23INP Temperature boundary between the columnar and equiaxed-grain zone [C]
* T34INP Temperature boundary between the equiaxed and unstructured-grain zone [C]
* G23INP Grain Size defining the boundary between columnar and equiaxed zones [mm]
* G34INP Grain Size defining the boundary between equiaxed
*          and unstructured zones [mm]
* P23INP Pore migration length for the boundary between columnar
*          and equiaxed zones [mm]
* P34INP Pore migration length for the boundary between equiaxed
*          and unstructured zones [mm]
*
* t23inp  t34inp  g23inp  g34inp  p23inp  p34inp
*-----+-----+-----+-----+-----+-----+-----+-----+
* 0.        0.        0.        0.        0.        0.
*-----+-----+-----+-----+-----+-----+-----+
* format:8F10.5
*
*****
*
* FASTLF Fast leakage factor only relevant for the RADAR model (iform = 2)
* RESESC Resonance escape probability only relevant for the RADAR model (iform = 2)
*
* fastlf  resesc
*-----+-----+-----+-----+
* 0.        0.
*-----+-----+-----+-----+

```

```

* format:2F10.5
*
*****
*
* CANF(I) Initial fill gas concentrations ( / )
*
* canf(1:10)
*He      Ar      Kr      Xe      N2      H2      O2      CO      CO2      H2O
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
1.      0.      0.      0.      0.      0.      0.      0.      0.      0.
*-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:10F8.5
*
*****
*
* HHREF(L) Reference heights of axial slices [mm]
*
* hhref(1), l=1,m31
*-----+-----+-----+-----+-----+-----+-----+-----+-----+
107.5
*-----+-----+-----+-----+-----+-----+-----+-----+-----+
* format:8F10.5
*
*****
*
* AEAX1 Input mode for radial discretization
*
* ---+-----+-----+-----+-----+-----+-----+-----+-----+
0
* ---+-----+-----+-----+-----+-----+-----+-----+-----+
* format:I5
*
*****
*
* AEGROB Mode for radial discretisation of coarse zones
* AEFEIN Mode for radial discretisation of fine zones
* M1      Number of coarse zones in (fuel + cladding)
* M1H     Number of coarse zones in cladding
*
* aegrob m1
* aefein mlh
* ---+---+---+---+-----+-----+-----+-----+-----+
0 0 5 5
* ---+---+---+---+-----+-----+-----+-----+-----+
* format:4I5
*
*****
*
* IFALLL(L)=1 Analysis of cladding only
*
* ifalll(1)
* ---+-----+-----+-----+-----+-----+-----+-----+-----+
1
* ---+-----+-----+-----+-----+-----+-----+-----+-----+
* format:I5
*
*****
*
* M2(IGROB) Number of mesh points per coarse zone
*
* ---+---+---+---+---+-----+-----+-----+-----+-----+
2 2 2 2 2
* ---+---+---+---+---+-----+-----+-----+-----+-----+
* format:16I5
*
*****
*
* RIB      Inner fuel radius [mm]
* RAB      Outer fuel radius [mm]
* RIH      Inner cladding radius [mm]
* RAH      Outer cladding radius [mm]
* Raubl    Surface roughness fuel [mm]

```



```

* Rauhl    Surface roughness clad [mm]
*
* rih      rah      ! Only cladding is simulated
*-----+-----+-----+-----+-----+-----+
4.645      5.375
*-----+-----+-----+-----+-----+-----+
* format:8F10.5
*
*****
*****
*
* IVAR1     Calculation mode for inner pin pressure
*
*-----+-----+-----+-----+-----+-----+
      2      ! pin pressure is calculated f(T,moles of gas)
*-----+-----+-----+-----+-----+-----+
* format:I5
*
*
* PI0EIN    Fillgas pressure [MPa]
* TI0EIN    Fillgas temperature [C]
* UPLVG     Lower plenum volume (maximum) [mm**3]
* AUPL      Volume fraction factor in lower plenum
* AOPL      Volume fraction factor in upper plenum
* ASP       Volume fraction factor in gap
* AZK       Volume fraction factor in central void
*
* pi0ein    ti0ein    uplv    aupl    aopl    asp    azk
*-----+-----+-----+-----+-----+-----+-----+
*1.0        20.        0.0      1.      1.      1.      1.
23.67374    400.        0.0      1.      1.      1.      1.
*-----+-----+-----+-----+-----+-----+
* format:8F10.5
*
*****
*****
* Macrostep Part - Label IMAK followed by 4 dummy lines
* *****
*
IMAK

*****
*
*
*      Time Step
*      0 h
*
*-----+-----+-----+-----+-----+-----+
* iwert
*      iaxvar
*      zeit      wert      dwert
*-----+-----+-----+-----+-----+-----+
*
* 1: print out of the results
*-----+-----+-----+-----+-----+-----+
01      0      0.      0.
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*
*
* 2: linear rod power (kW/m)
*-----+-----+-----+-----+-----+-----+
      2      0      .0000000000000D+00      .0000000000000D+00
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*
*
* 4: coolant flow rate (g/h)
*-----+-----+-----+-----+-----+-----+

```

```

      4      0      .000000000000D+00      0.
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*      9: coolant temperature (C)
*-----+-----+-----+-----+-----+-----+
      9      0      .000000000000D+00      400.000000000D+00
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     10: coolant pressure (MPa)
*-----+-----+-----+-----+-----+-----+
      10      0 0.                                0.1
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     18: equivalent outer diameter (mm)
*-----+-----+-----+-----+-----+-----+
      18      0 0.                                30.
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     21: rod internal pressure
*-----+-----+-----+-----+-----+-----+
      21      0      .000000000000D+00      2.357000000D+01
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     25: Time step control factor for explicit creep
*-----+-----+-----+-----+-----+-----+
      25      0      .000000000000D+00      .10000000000D+00
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     26: lower time step limit
*-----+-----+-----+-----+-----+-----+
      26      0      .000000000000D+00      .10000000000D-29
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*     30: write macro plot data
*-----+-----+-----+-----+-----+-----+
      30      0      .000000000000D+00      .00000000000D+00
*-----+-----+-----+-----+-----+-----+
* format:2I5,2D20.13,D10.3
*
*-----+-----+-----+-----+-----+-----+
*
*      time = 240 h
*-----+-----+-----+-----+-----+-----+
      2      0 2.4D+02                        .00000000000D+00
      4      0 2.4D+02                        .00000000000D+00
      9      0 2.4D+02                        4.00000000000D+02
     10      0 2.4D+02                        .10000000000D+00
     30      0 2.4D+02                        .00000000000D+00
*-----+-----+-----+-----+-----+-----+
*
*      time = 400 h
*-----+-----+-----+-----+-----+-----+
      2      0 4.0D+02                        .00000000000D+00
      4      0 4.0D+02                        .00000000000D+00
      9      0 4.0D+02                        4.00000000000D+02
     10      0 4.0D+02                        .10000000000D+00

```

```

30    0 4.0D+02                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 800 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 8.0D+02                .0000000000000D+00
4     0 8.0D+02                .0000000000000D+00
9     0 8.0D+02                4.0000000000000D+02
10    0 8.0D+02                .1000000000000D+00
30    0 8.0D+02                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 1500 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 1.5D+03                .0000000000000D+00
4     0 1.5D+03                .0000000000000D+00
9     0 1.5D+03                4.0000000000000D+02
10    0 1.5D+03                .1000000000000D+00
30    0 1.5D+03                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 3000 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 3.0D+03                .0000000000000D+00
4     0 3.0D+03                .0000000000000D+00
9     0 3.0D+03                4.0000000000000D+02
10    0 3.0D+03                .1000000000000D+00
30    0 3.0D+03                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 5000 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 5.0D+03                .0000000000000D+00
4     0 5.0D+03                .0000000000000D+00
9     0 5.0D+03                4.0000000000000D+02
10    0 5.0D+03                .1000000000000D+00
30    0 5.0D+03                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 7500 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 7.5D+03                .0000000000000D+00
4     0 7.5D+03                .0000000000000D+00
9     0 7.5D+03                4.0000000000000D+02
10    0 7.5D+03                .1000000000000D+00
30    0 7.5D+03                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
*
*   time = 10000 h
*-----+-----+-----+-----+-----+-----+-----+-----+
2     0 1.0D+04                .0000000000000D+00
4     0 1.0D+04                .0000000000000D+00
9     0 1.0D+04                4.0000000000000D+02
10    0 1.0D+04                .1000000000000D+00
30    0 1.0D+04                .0000000000000D+00
*-----+-----+-----+-----+-----+-----+-----+-----+
* End of Input
*-----+-----+-----+-----+-----+-----+-----+-----+
0     0 1.0D+04                0.0000000000000D+00

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European Commission

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Title: Creep Simulations of Nuclear Fuel Cladding under long term Storage Conditions with TRANSURANUS

Author(s): MARTIN Oliver, NILSSON Karl-Fredrik, GYORI Csaba, VAN UFFELEN Paul, SCHUBERT Arndt.

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Abstract

Within a joint research project between the Institute for Energy (IE) and the Institute for Transuranium Elements (ITU) on the integrity of spent nuclear fuel cladding the ITU code TRANSURANUS was used to simulate creep of Zircaloy cladding tubes under long term storage conditions. Since TRANSURANUS is designed to model the mechanical, thermal and physical behaviour of fuel rods during reactor operation it was the objective of this study firstly to explore the limitations of the present creep models in TRANSURANUS for the simulation of long term creep processes under dry storage conditions. If the present creep models in TRANSURANUS were found to be inappropriate then the next objective was to formulate the properties of an "ideal" creep model for dry storage. The creep models were compared with creep tests on unirradiated Zircaloy cladding tubes. It turned out that the standard creep model for Zircaloy cladding in TRANSURANUS, the model of Laßmann and Moreno, underestimated the creep strains of the tests significantly. The creep model of Mayuzumi and Onchi, which was designed to model long term creep processes under dry storage conditions, lead to reasonable agreement with the creep tests for temperatures of 350°C and above. It turned out that for the accurate prediction for low-temperature conditions (under 350°C) more sophisticated creep models, which account for a shift in creep mechanisms, are necessary.

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